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FACTORS CONTROLLING THE DISTRIBUTION OF FOREST TYPES, PART I[1]

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Forest Examiner, Fort Valley Experiment Station

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INTRODUCTION

Every student of plant life in our western mountain regions is familiar with the altitudinal zonation which characterizes the distribution of the forest trees. To the forester this phenomenon is of great significance, since it enables him to determine offhand what species to expect at any altitude on a slope of a given aspect. To the student of problems concerning the growth and perpetuation of forests it affords an excellent opportunity for studying the soil and climatic requirements of different species. The presence or absence of certain species at certain altitudes and slope exposures is immediately associated with temperature, moisture, and other factors prevailing on these sites. It is a matter of common knowledge that as a rule the temperature is lower and the rainfall higher in the mountains than in the valleys below, and therefore it has been assumed that the trees normally occurring at high altitudes have relatively high moisture requirements and low temperature requirements, while those occurring at low altitudes have relatively low moisture requirement and high temperature requirements.

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[1] Based upon Studies in the San Francisco Mountains of Arizona. [The word forest "type" was used by foresters in practically the same sesne that "association" is now used by many ecologists long before the latter term originated, and still continues in good usage.—EDITOR.]

Investigations by Bates[2] in the Central Rocky Mountains yield conclusions at variance with the above conception as regards moisture requirements. His experiments indicate that the species inhabiting dry sites, such as western yellow pine, utilize more moisture in the production of a unit of dry matter than do the species occupying relatively humid sites, *e.g.*, Douglas fir and Engelmann spruce. These findings may strike the reader as being revolutionary, but a moment's reflection will show them to be in accord with actual conditions. In the San Francisco Mountains, the Engelmann spruce forests receive approximately 50 percent more precipitation than do the yellow pine forests. The average spruce stand, however, yields roughly 25,000 board feet of saw timber per acre in 100 years against about 8,000 board feet of yellow pine in 200 years. Thus the spruce appears to be about six times as economical in water consumption as is yellow pine. A large part but by no means all of this difference may be accounted for by the greater loss through direct evaporation in the yellow pine type.

Of greater importance than the moisture requirement as related to the production of dry matter is the moisture required for normal development. A species with high requirements per unit of material produced may, by reason of its slow growth, be able to maintain itself where the species of lower requirements in proportion to material produced can not exist. Moreover, we must also consider the capacity of a plant for obtaining water, as determined by its normal root spread. It is a matter of common observation that species occupying dry sites usually have a much greater root.area than species occupying relatively moist sites. This relation is amply illustrated by western yellow pine and Engelmann spruce. To what extent root habit is a fixed character is a matter on which our knowledge is limited.[3] It may well be doubted, however, whether Engelmann spruce would under any conditions be able to attain the depth and spread of root exhibited by western yellow pine. If such be the case, it is conceivable that yellow pine on a dry site, even with its relatively high demands, might be able to more fully satisfy its needs for moisture than Englemann spruce with its lower requirements.

Looking at the matter in this light, the common conception regarding moisture requirements, namely, that the species of highest requirements occupy the most humid climatic zones, is probably correct. As regards temperature requirements, the usual assumption that the species occupying the warmest sites are there because they require high temperature for normal development, seems to be generally accepted, though it is conceivable that this may not necessarily be the case. Foresters must recognize that this field is still undeveloped and that exhaustive studies may be expected to yield a wealth of information. With this situation in view an investigation known as "The Study of Forest Types" has been undertaken by the Forest Service in various sections of the West. In brief, the object has been to correlate the occurrence of tree species with physical environment in different forest types or associations, and thus to determine what conditions are favorable and what unfavorable to each species. Such a study has been in progress at the Fort Valley Experiment Station in the San Francisco Mountains of Arizona during the past two years. The principles here developed are, according to the writer's observations, applicable to the entire Southwest, although it is recognized that they may be subject to more or less modification under conditions peculiar to certain localities. Although the study is still incomplete, sufficient progress has been made to warrant a preliminary presentation of results.

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[2] Bates, C. G., "Forest Types of the Central Rocky Mountains" (being published by the U. S. Weather Bureau).

[3] For interesting material on the root habit of certain forest trees see Pulling, N. E., "Root Habit and Plant Distribution in the Far North," Plant World, Vol. 21, No. 9, pp. 223–233, 1918.

Waterman, W. G., "Development of Root Systems under Dune Conditions," Bot. Gaz., Vol. 68, No. 1, pp. 22–53, 1918, finds some rather striking relations between root spread and the chemical composition of soils.

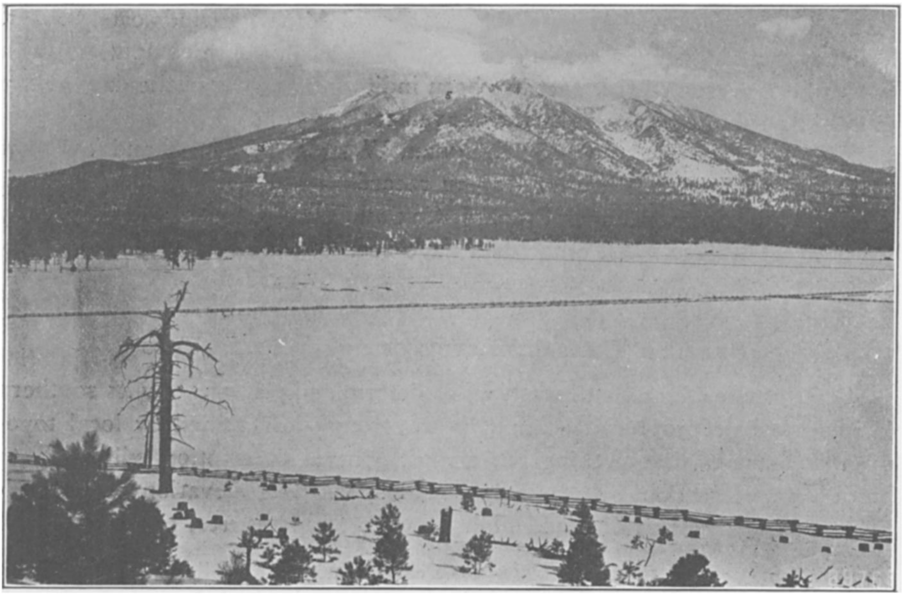

FIG. 1. The San Francisco Mountains with Fort Valley in the foreground. The numbers indicate the location of the meteorological stations as follows: 1, yellow pine; 2, Douglas fir; 3, limber pine; 4, Engelmann spruce; 5, timber line.

Before proceeding with the discussion, a brief statement of the general circumstances under which the study has been conducted is in order.

First, the writer desires to acknowledge the services of his associates at the Fort Valley Experiment Station. An understanding of the physical difficulties presented by this investigation may be gained when it is considered that for over two years weekly or semi-weekly trips have been made from the Experiment Station headquarters to timberline, involving a climb of over 4,000 feet. In the winter this climb is often hazardous and calls for great physical endurance.[4]

Due to various circumstances, the records at the high altitude stations have occasionally been broken. This applies particularly to the timberline station which has been inaccessible during considerable periods each winter. Whenever it has been necessary to use incomplete data in computing mean values here presented this fact has been indicated, and when the data are so meager as to be untrustworthy they have been omitted.

The meteorological data for Kingman, Williams, Flagstaff and Winslow are taken from U. S. Weather Bureau records. The records for Ash Fork were kept by Forest Ranger Frank J. Cox and those for Walnut Canyon by Mrs. W. H. Pierce. All other data have been obtained directly by the Experiment Station.

Physical Characteristics of the Forest Types

The climate of the Southwest, while determined primarily by its southern latitude and geographical location, is so strongly diversified by local topographic features that nothing but a most general description will apply to any extensive section. Areas below 4,000–5,000 feet elevation are characterized by extreme aridity and high summer temperatures, associated with desert vegetation. As the higher altitudes are reached there is a gradual increase in precipitation and decrease in temperature accompanied by added luxuriance in vegetation which culminates in magnificent spruce forests at 10,000 to 11,000 feet elevation. Latitude is distinctly subordinate to altitude in determining climatic variations within this region.

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[4] The primary instrument stations were established in the fall of 1916 by Forest Assistants Emanuel Fritz and Lenthal Wyman who maintained the records through the following winter and spring. During the summer and fall of 1917 observations were continued successively by Forest Assistants T. S. Hansen, C. E. Behre and S. S. Van Boskirk. From December, 1917, to July, 1918, the work was carried on by Forest Ranger Landis J. Arnold, and from July, 1918, to May, 1919, by Forest Ranger J. E. Kintner. During this entire period, the writer has maintained close supervision over the work, and at intervals, in the absence of assistance, has handled it in person. Since June, 1918, the formidable task of compiling the data has been greatly facilitated by the efficient service of Forest Clerk Miss Maude E. Wilson, whose work has made it possible to keep the compilations well up to date. Mr. J. O. Veatch, of the Bureau of Soils, has rendered valuable assistance in the classification of soils. His work, which promises to yield rich returns, is just beginning as this article is being completed. Grateful acknowledgment is also made to Mr. Raphael Zon, Chief of Forest Investigations of the Forest Service, for his many helpful suggestions and his unfailing encouragement throughout this investigation. The frequent changes in personnel indicated by the numerous assignments to this project are due to war conditions. Obviously the work has suffered from these changes.

The territory covered by this study comprises an altitudinal range of 6,400 feet, extending from 5,100 to 11,500 feet elevation, within a horizontal distance of about 55 miles, and is generally typical of forest conditions on the Colorado Plateau. Foresters recognize five main forest types or plant associations which are distinguished by the predominant tree species. Their approximate altitudinal arrangement is as follows:

Forest Type	Altitude	Predominating Species
Pinon-juniper	5,000– 6,700	*Juniperus monosperma* (Engelm.) Sarg. *Juniperus utahensis* (Engelm.) Lemm. *Pinus edulis* Engelm.
Yellow pine	6,700– 8,300	*Pinus ponderosa scopulorum* Engelm.
Douglas fir	8,300– 9,500	*Pseudotsuga taxifolia* (Lam.) Britton *Pinus flexilis* James *Abies concolor* (Gord.) Parry *Populus tremuloides* Michx.
Engelmann spruce	9,500–11,500	*Picea engelmanni* Engelm. *Abies arizonica* Merriam *Pinus aristata* Engelm. *Populus tremuloides* Michx.
Alpine	Above 11,500	Trailing forms of *Picea engelmanni* and *Pinus aristata*

Anyone familiar with mountain conditions will understand that the above limits are only approximate. On the average they will run about 500 feet higher on south exposures and about 500 feet lower on north exposures. Moreover, there is more or less interlapping, thus forming a transition zone between types.

Using the Fort Valley Experiment Station (altitude 7,300 ft.) in the yellow pine type as a base, stations for the study of climate, soil, and vegetation were established in each forest type. In addition, a number of temporary substations have been established for the purpose of determining local variations within the type. Climatic studies include air temperature, precipitation, evaporation and wind movement. The soil studies include temperature and moisture content at different depths, and physical and chemical analyses. Studies of vegetation involve a listing of native species and also the cultivation of plants both indigenous and exotic. Weekly or semi-weekly readings have been made continuously for two years, excepting at the base stations where daily readings have continued over nine years. At all the primary stations continuous records of air temperature, and at some of the stations soil temperature, have been secured by means of thermographs.

All of the primary stations are located in typical forests of the character they are designed to represent. It is recognized that this necessitates reckoning with the influence of the forest itself. This course was adopted, however, because what is wanted is a knowledge of the conditions under which the trees actually grow. By means of check stations it is possible to establish reducing factors for different conditions of cover, slope, exposure, etc.

Thermometers and anemometers have with few exceptions been exposed at a height of eight feet above the ground. It is especially desirable to measure the conditions to which young growth is subjected, and these conditions could be secured better by placing the instruments close to the ground. But this was considered impractical because the deep snows would cover them. Check readings are, however, being made in order to establish a relation between surface temperature and that at eight feet. Evaporation has been measured mainly from free water surfaces by means of tanks 15 inches in diameter. Porous cup evaporimeters have been used to some extent, but their continuous use is interfered with by the occurrence of frost during the growing season, particularly in the spring and fall when evaporation is of greatest importance. Living plants have also been employed to a limited extent. Soil temperatures have been measured both with standard soil thermometers and with ordinary thermometers suspended in a tube at the desired depth. For depths exceeding 1 foot an ordinary metal pipe closed at both ends is used. Originally these pipes were also used for shallower depths, but on account of the possible effect of conduction by the metal, they have been replaced by wooden tubes.

TEMPERATURE.—Comparisons of the various forest types with respect to temperature are given in Tables 1 to 8 and figures 1 to 3. The usual relation between altitude and temperature holds here in a general way. The altitudinal mean temperature gradient from Kingman at 3,300 feet to timber line on the San Francisco Mountains at 11,500 during 1917 and 1918 was 3.68° F. for each 1,000 feet. Observations on other mountains, according to Hahn,[5] have given the following gradients: Pikes Peak 3.46° F.; Sierra Nevadas (Colfax, Placer Co., California) 4.12°; free air gradient Blue Hill Observatory 2.5°. Shreve[6] finds a gradient of 4.11° in the Santa Catalina Mountains of southern Arizona. As shown in figure 2, the fall in temperature in the San Francisco Mountains is by no means constant for a given rise in elevation. Comparing all the stations, the least difference is found between the yellow pine and Douglas fir stations, representing an altitudinal difference of 1,600 feet. In many instances the relation between these two stations has shown an actual inversion, the highest temperatures being found at the highest altitude. The same condition was found by Shreve in the Santa Catalina

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[5] Hann, J., "Handbuch der Klimatologie," p. 245.

[6] Shreve, Forrest, "The Vegetation of a Desert Mountain Range as Conditioned by Climatic Factors," Carnegie Inst. of Wash. Publ. 217, 1915.

Mountains between 2,000 and 4,000 feet. Analysis of the records shows that the irregularities in the temperature gradient are due mainly to irregularities in the minimum. The maximum shows a very uniform gradient.

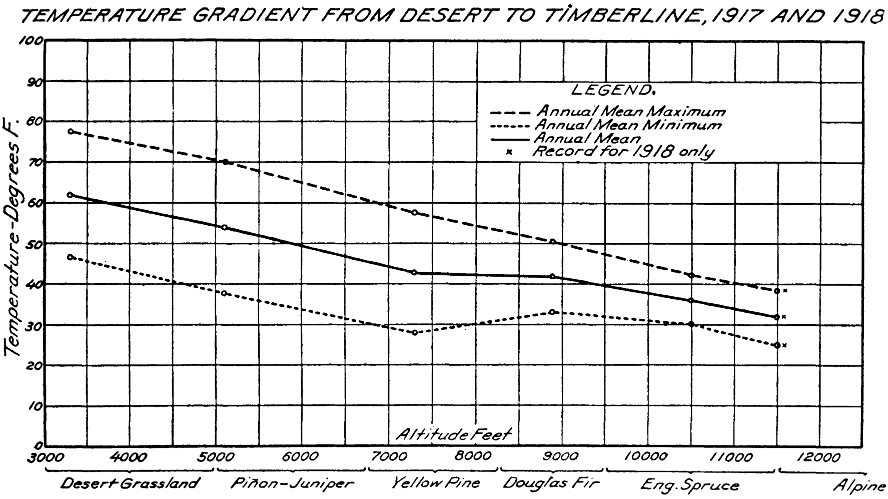

FIG. 2.

The erratic behavior of minimum temperatures in relation to altitude is one of the most striking things brought out in this study, although similar conditions have been found elsewhere. Extreme minimum temperatures are usually lower in the yellow pine type than at any of the higher stations, even

TABLE 1. *Temperature, annual and growing season. Means 1917 and 1918, degrees F.*

Forest type	Annual				June–September		
	Alt. Ft.	Mean	M. Max.	M. Min.	Mean	M. Max.	M. Min.
Desert-Grassland							
Kingman	3,300	62.1	77.5	46.6	79.9	95.3	64.4
Winslow	4,850	53.8	......	......	73.0	90.8	55.2
Pinon-Juniper							
Ash Fork	5,100	54.2	70.2	38.1	71.1	87.6	54.6
Cosnino[a]	6,500	......	......	......	65.6	82.4	48.8
Yellow Pine							
Williams	6,750	47.4	63.5	31.3	65.6	82.1	49.1
Walnut Canyon	6,700	......	......	......	64.8	82.3	47.4
Flagstaff	6,900	44.2	59.0	29.4	61.4	77.2	45.7
Fort Valley	7,300	42.5	57.6	27.4	59.5	75.3	43.8
Douglas Fir	8,900	41.7	50.5	33.0	56.9	67.1	46.6
Engelmann Spruce	10,500						
N. W. Slope, cover	....	36.0	42.1	29.9	51.4	58.2	44.5
S. W. Slope, open[ab]	....	37.5	45.0	30.0	52.0	61.2	42.8
Alpine[ab]	11,500	31.9	38.6	25.1	47.8	55.1	40.4

[a] 1918 record only.
[b] Interpolated in part.

TABLE 2. *Mean temperature by months, 1917 and 1918, degrees F.*

Forest type	Jan.	Feb.	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Desert-Grassland													
Kingman[a]	41.4	46.2	51.2	58.5	61.9	78.9	83.4	80.4	77.1	65.2	53.0	47.3	62.1
Winslow	28.4	38.8	44.0	51.1	58.3	73.3	76.9	73.8	67.7	56.7	42.8	33.3	53.8
Pinon-Juniper													
Ash Fork[b]	34.3	38.1	42.6	50.3	54.9	71.3	74.4	71.2	67.8	58.3	46.5	40.9	54.2
Yellow Pine													
Williams	27.0	33.3	37.3	43.1	48.8	64.8	67.8	64.0	61.0	49.8	38.9	33.5	47.4
Flagstaff	23.5	29.5	33.6	40.3	45.6	62.1	64.6	61.8	57.2	48.1	34.8	30.2	44.3
Fort Valley	23.1	27.5	30.4	37.7	42.5	59.9	62.3	60.3	55.8	47.1	34.1	29.5	42.5
Douglas Fir	24.6	27.7	30.7	37.3	41.7	60.1	58.1	56.3	53.2	46.7	34.5	30.8	41.8
Engelmann Spruce	20.8	21.5	23.5	29.6	34.6	52.9	52.6	52.4	47.8	41.4	29.4	26.1	36.0
Alpine[c]	15.7	17.2	23.1	26.2	30.8	51.6	48.1	46.8	44.7	35.4	23.5	19.3	31.8

[a] Incomplete for April, July, September and October, 1917. Interpolated for March, 1917.

[b] Incomplete for January, October and November, 1917.

[c] Records for 1918 only. Incomplete for February, March, November and December.

TABLE 3. *Mean maximum temperature by months, 1917 and 1918, degrees F.*

Forest Type	Jan.	Feb.	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Desert-Grassland													
Kingman[a]	54.3	60.9	67.8	76.3	78.2	98.0	98.3	94.6	90.6	82.4	67.5	61.6	77.5
Pinon-Juniper													
Ash Fork[b]	48.6	50.1	57.2	66.6	70.2	90.1	89.6	86.4	84.5	76.7	65.2	58.3	70.3
Yellow Pine													
Williams	40.7	45.7	51.5	59.0	63.4	84.8	83.9	81.2	78.6	68.8	55.7	49.1	63.5
Flagstaff	37.6	41.2	46.7	54.4	59.8	80.2	78.3	76.6	73.1	64.9	50.5	45.5	59.1
Fort Valley	37.4	40.0	44.3	51.8	57.2	78.0	76.6	75.1	71.7	64.0	49.6	45.5	57.6
Douglas Fir	30.1	34.6	39.0	46.3	52.4	72.1	67.5	66.3	62.8	56.1	42.0	37.3	50.5
Engelmann Spruce	25.9	26.2	29.9	36.6	42.6	61.1	59.4	58.7	53.8	46.6	34.6	30.3	42.1
Alpine[c]	21.6	24.0	29.0	34.1	38.9	59.5	54.9	53.8	52.2	41.2	30.0	23.5	38.5

[a] Incomplete for April, July, September, October, 1917. Interpolated for March, 1917.

[b] Incomplete for January, October, November, 1917.

[c] Records for 1918 only. Incomplete for February, March, November and December.

timber line (Table 7). Above and below the yellow pine type the trend is normal. The low temperatures in the yellow pine are due to air drainage; cold air currents descend from the high mountain slopes and spread out over the mesas and valleys below. Previous investigations in this region[7] have shown that in valleys, particularly where devoid of forest cover, minimum temperatures are commonly 10 to 15 degree lower than on nearby timbered uplands. The descent from the yellow pine to the pinon-juniper type is accompanied by a gradual rise in minima and a very rapid rise in maxima.

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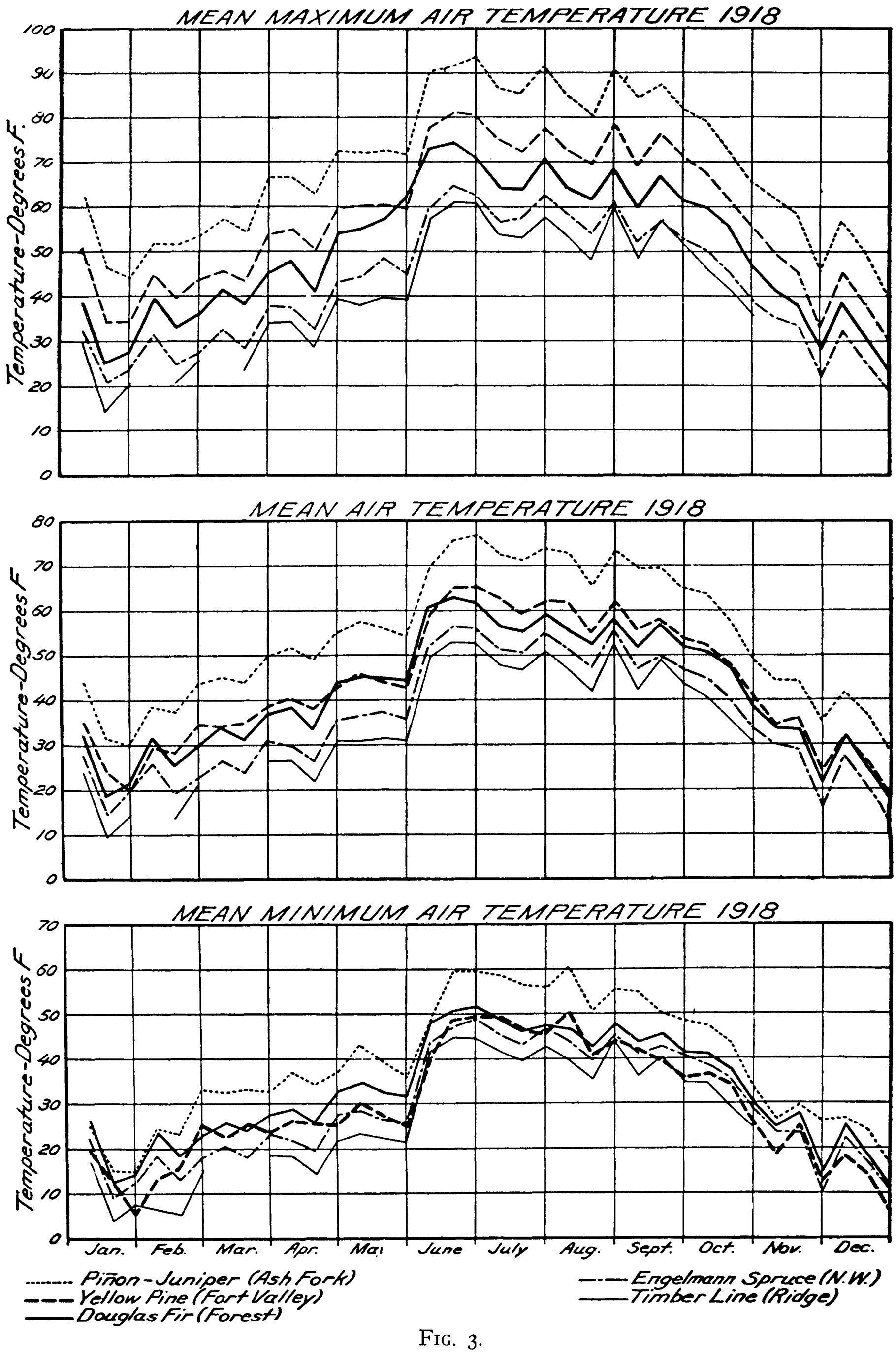
[7] Pearson, G. A., "A Meteorological Study of Parks and Timbered Areas in the Western Yellow Pine Forests of Arizona and New Mexico," Monthly Weather Review, Vol. 41, pp. 1615–29, 1914.


MEAN MAXIMUM AIR TEMPERATURE 1918
Temperature-Degrees F.
100
90
80
70
60
50
40
30
20
10
0
MEAN AIR TEMPERATURE 1918
Temperature-Degrees F
80
70
60
50
40
30
20
10
0
MEAN MINIMUM AIR TEMPERATURE 1918
Temperature-Degrees F
70
60
50
40
30
20
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0
Jan.
Feb.
Mar.
Apr.
Mai
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Piñon-Juniper (Ash Fork)
Yellow Pine (Fort Valley)
Douglas Fir (Forest)
Engelmann Spruce (N.W.)
Timber Line (Ridge)

FIG. 3.

TABLE 4. *Mean minimum temperature by months, 1917 and 1918, degrees F.*

Forest type	Jan.	Feb.	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Desert-Grassland													
Kingman[a]	28.4	31.5	34.7	40.7	45.7	59.9	68.6	66.2	63.7	48.1	38.4	33.0	46.6
Pinon-Juniper													
Ash Fork[b]	19.9	26.0	28.0	33.9	39.5	52.5	59.1	56.0	51.0	39.9	27.8	23.4	38.1
Yellow Pine													
Williams	13.2	20.8	23.0	27.2	34.2	44.7	51.7	46.7	43.4	30.8	22.0	17.8	31.3
Flagstaff	9.4	17.8	20.5	26.2	31.3	43.9	50.8	47.0	41.2	31.3	19.1	14.9	29.5
Fort Valley	8.8	14.9	16.4	23.6	27.7	41.7	47.9	45.5	39.9	30.2	18.5	13.5	27.4
Douglas Fir	19.0	20.8	22.3	28.3	31.0	48.1	48.7	46.3	43.6	37.2	27.0	24.2	33.0
Engelmann Spruce	15.7	16.8	17.1	22.6	26.5	44.6	45.8	46.0	41.7	36.2	24.2	21.8	29.9
Alpine[c]	9.7	10.3	17.3	18.3	22.7	43.6	41.3	39.7	37.1	29.6	17.0	15.0	25.1

[a] Incomplete for April, July, September, October, 1917. Interpolated for March, 1917.

[b] Incomplete for January, October, November, 1917.

[c] Records for 1918 only. Incomplete for February, March, November and December.

TABLE 5. *Mean daily range of temperature by months, 1917 and 1918, degrees F.*

Forest type.	Jan.	Feb.	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Desert-Grassland													
Kingman[a]	25.9	29.4	33.1	35.6	32.5	38.1	29.7	28.4	26.9	34.3	29.1	28.6	30.9
Pinon-Juniper													
Ash Fork[b]	28.7	24.1	29.2	32.7	30.7	37.6	30.5	30.4	33.5	36.8	37.4	34.9	32.2
Yellow Pine													
Williams	27.5	24.9	28.5	31.8	29.2	40.1	32.2	34.5	35.2	38.0	33.7	31.3	32.2
Flagstaff	28.2	23.4	26.2	28.2	28.5	36.3	27.5	29.6	31.9	33.6	31.4	30.6	29.6
Fort Valley	28.6	25.1	27.9	28.2	29.5	36.3	28.7	29.6	31.8	33.8	31.1	32.0	30.2
Douglas Fir	11.1	13.8	16.7	18.0	21.4	24.0	18.8	20.0	19.2	18.9	15.0	13.1	17.5
Engelmann Spruce	10.2	9.4	12.8	14.0	16.1	16.5	13.6	12.7	12.1	10.4	10.4	8.5	12.2
Alpine[c]	11.9	13.7	11.7	15.8	16.2	15.9	13.6	14.1	15.1	11.6	13.0	8.5	13.4

[a] Incomplete for April, July, September, October, 1917. Interpolated for March, 1917.

[b] Incomplete for January, October, November, 1917.

[c] Records for 1918 only. Incomplete for February, March, November and December.

TABLE 6. *Frostless period*

Forest type	Alt.	First and last killing frost				Length of frostless period (days)	
		1917		1918			
		Spring	Fall	Spring	Fall	1917	1918
Desert-Grassland							
Kingman	....	4/18	11/30	......	......	226	......
Pinon-Juniper							
West (Ash Fork)	5,100	6/1	10/19	5/30	10/18	140	140
East (Cosnino)	6,500	......	......	5/31	9/24	......	116
Yellow Pine							
Walnut Canyon	6,700	6/6	9/27	5/31	9/24	113	116
Flagstaff	6,900	6/6	9/27	5/31	9/24	113	116
Fort Valley	7,300	6/12	9/25	5/31	9/17	105	109
Douglas Fir	8,900	6/2	10/18	5/31	10/18	137	140
Engelmann Spruce	10,500	6/5	9/24	5/31	9/25	111	117
Alpine	11,500	6/5	9/23	6/1	9/23	110	114

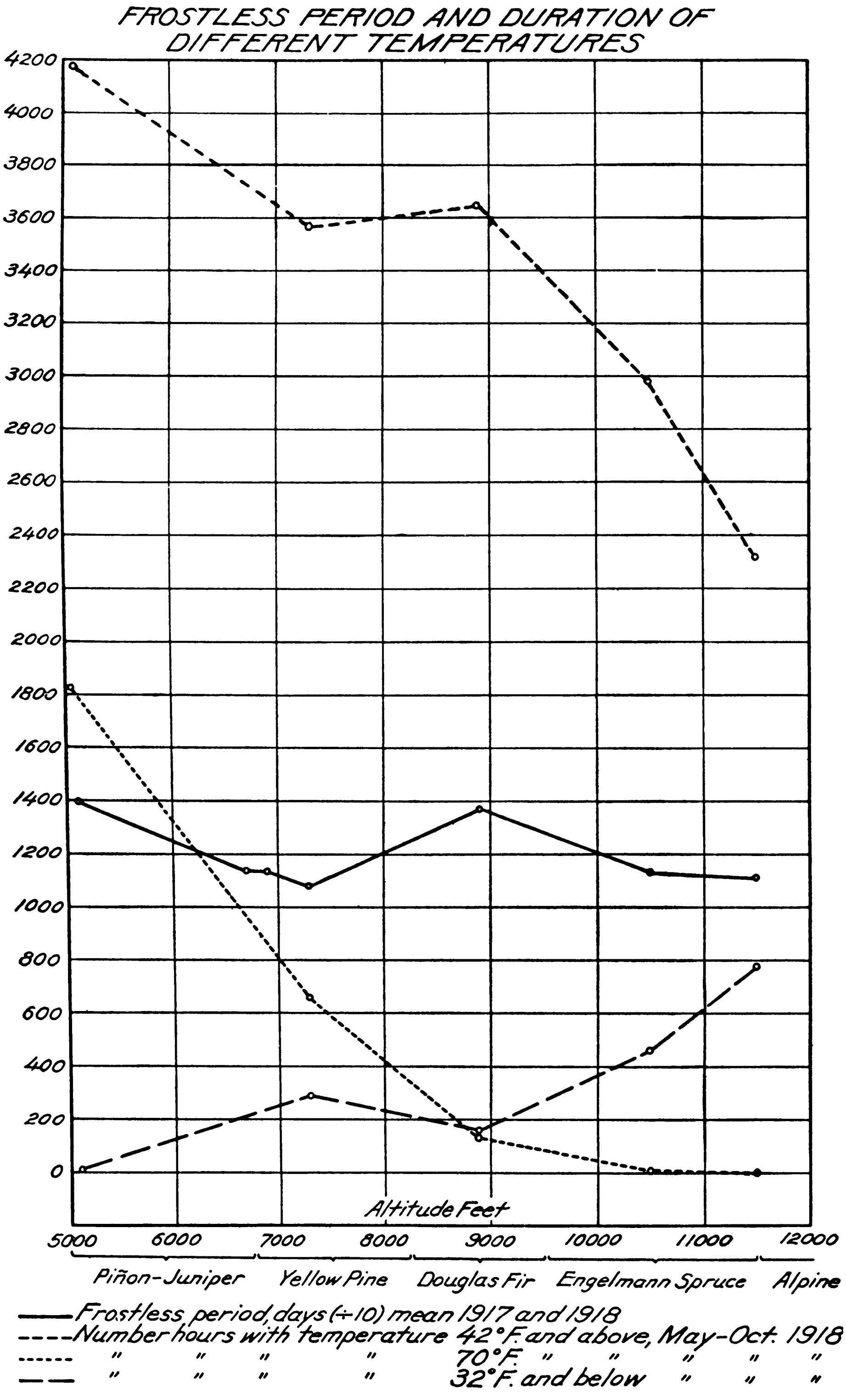
FROSTLESS PERIOD AND DURATION OF DIFFERENT TEMPERATURES
4200
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Altitude Feet
5000
6000
7000
8000
9000
10000
11000
12000
Piñon-Juniper
Yellow Pine
Douglas Fir
Engelmann Spruce
Alpine
——Frostless period, days (÷10) mean 1917 and 1918
----Number hours with temperature 42°F. and above, May-Oct. 1918
------ " " " " 70°F. " " " " "
— — " " " " 32°F. and below " " "

FIG. 4.

The length of the frostless period as determined by the occurrence of temperature below 32° F. is shown in Table 6 and figure 4. It is noteworthy that the shortest frostless season occurs at stations in the yellow pine type. Even in the alpine type the first killing frost in the fall of 1918 occurred a week later than at the Fort Valley Station in the yellow pine type. The Douglas fir type has the longest frostless period of the high mountain types; in 1918 is was as long as at Ash Fork, nearly 4,000 feet lower.

TABLE 7. *Lowest temperatures by months, 1918, degrees F.*

Forest type	Jan.	Feb.	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Desert-Grassland												
Kingman.....	21.0	21.0	28.0	27.0	35.0	49.0	53.0	50.0	51.0	38.0	24.0	11.0
Winslow......	− 9.0	12.0	18.0	17.0	30.0	40.0	52.0	44.0	38.0	23.0	14.0	− 1.0
Pinon-Juniper												
Ash Fork.....	0	14.0	23.0	24.0	31.0	41.0	50.0	46.0	37.0	27.0	11.0	9.0
Yellow Pine												
Williams.....	− 3.0	2.0	12.0	18.0	21.0	28.0	39.0	35.0	26.0	18.0	0	− 7.0
Flagstaff.....	−13.0	3.0	11.0	16.0	18.0	32.0	42.0	36.0	25.0	16.0	− 4.0	−10.0
Fort Valley...	− 6.0	−13.0	6.0	15.0	12.0	33.0	40.0	34.0	25.0	15.0	− 4.0	−10.0
Douglas Fir.....	− 2.0	4.0	14.0	18.0	23.0	39.0	43.0	41.0	33.0	20.0	8.0	− 2.0
Engelmann												
Spruce.......	− 6.0	2.0	9.0	13.0	19.0	35.0	39.0	38.0	32.0	17.0	2.0	− 6.0
Alpine.........	− 3.0	− 2.0	9.0	5.0	13.0	30.0	34.0	33.0	29.0	10.0	2.0	......

Invariably the highest temperatures occur in the lowest altitudes (Table 3). In the spruce and alpine types temperatures above 70° F. are exceedingly rare, but in the yellow pine and pinon-juniper they are common from May to September. An idea of the relative duration of high temperature is obtained by comparing the stations with respect to the number of hours of temperature above 70° F. (table 8). For all excepting the pinon-juniper stations, the May–October total is also the annual total.

The daily range is greatest in the lower altitudes. In the pinon-juniper and yellow pine types we commonly find a daily range of 40 to 50 degrees, while in the spruce and alpine types it is rarely more than 20 (Table 5).[8]

The salient facts in regard to air temperature may be summarized as follows:

Mean temperature decreases as the altitude increases, except for local inversions in the gradient which occur rather frequently between the yellow pine and Douglas fir types. Departures from the general law are due

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[8] [This is the reverse of the conditions found in the Alps by Bonnier ("Le Monde végétal," E. F. Flammarion, Paris, 1914, p. 336), and indicated by brief records on Mt. Marcy, New York ("Plants and Animals of Mount Marcy, New York, Part I," Ecology, Vol. 1, No. 2, 1920). The reason is probably the dryness of the lower elevation in Arizona. The increase of moisture with altitude in Arizona would tend to counterbalance the decreased atmosphere and increased insolation, and thereby diminish the diurnal range of temperature. In a pluvial climate such as that of the Alps and eastern United States moisture does not increase so markedly with altitude.—EDITOR.]

TABLE 8. *Duration of different temperatures, 1918. Number of hours*

Forest type	32° F. or below		42° F. or above	70° F. or above	
	May–Oct.	June–Sept.	May–Oct.	June–Sept.	Annual
Pinon-Juniper					
Ash Fork	13 plus	0	4,177	1,489	1,872 plus
Yellow Pine					
Fort Valley	287	21	3,565	633	657
Douglas Fir	158	0	3,650	134	134
Engelmann Spruce	461	0	2,977	4	4
Alpine	779	24	2,324	1	1

to low minimum temperatures in the yellow pine type resulting from the descent of cold air currents from the upper mountain slopes. The lowest absolute minima and the shortest frostless period usually occur in the yellow pine type, followed closely by the alpine type. The highest temperatures and greatest duration of high temperature are found in the lowest altitudes. Maximum temperatures decrease uniformly from the lowest to the highest altitudes. The greatest daily range occurs in the lower types; in the spruce and alpine types, temperatures are very constant.[9]

PRECIPITATION.—Annual precipitation increases rapidly with altitudes up to the Douglas fir types (Table 9 and fig. 5). From there on to about 10,500 feet it remains nearly stationary, but beyond this point there appears to be a still further substantial increase. Considerable variability is exhibited in the relation between the upper stations. Thus in 1917, the Engelmann spruce station showed a slight excess over the Douglas fir station, while in 1918 the relation was reversed. Several years will be required to give a reliable comparison. As a rule records in other regions have shown a slight decrease from the intermediate to the highest elevations. The annual distribution is about the same for the various types. At the Fort Valley Experiment Station, where records have been maintained for nine years, the distribution is roughly as follows: winter (December–March), 40 percent; spring (April–May) 10 percent; summer (June–August) 30 percent; autumn (September–November) 20 percent.

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[9] [It would have been interesting if summations of temperature according to Merriam's plan or Lehenbauer's physiological method had been added. Sampson in his "Climate and Plant Growth in Certain Vegetative Associations," U. S. Dept. Agr. Bul. 700, 1918, states that such summations "have shown much promise in correlating air temperature with physiological plant activities." In a study of the factors causing timber line on mountains data was secured which, though insufficient for final conclusions, suggested that effective temperature may be the leading factor in causing timber line (see "Plants and Animals of Mount Marcy, Part I" p. 92; Ecology Vol. I, No. 2, 1920). It is interesting that in Pearson's table 8 giving the duration of different temperatures, the alpine had 653 hours, or 23 percent less, above 42° F. than the Engelmann spruce, and that this is the largest percentage decrease between any of the types. It is possible that this relationship would have been even more striking in a summation of effective temperature.—EDITOR.]

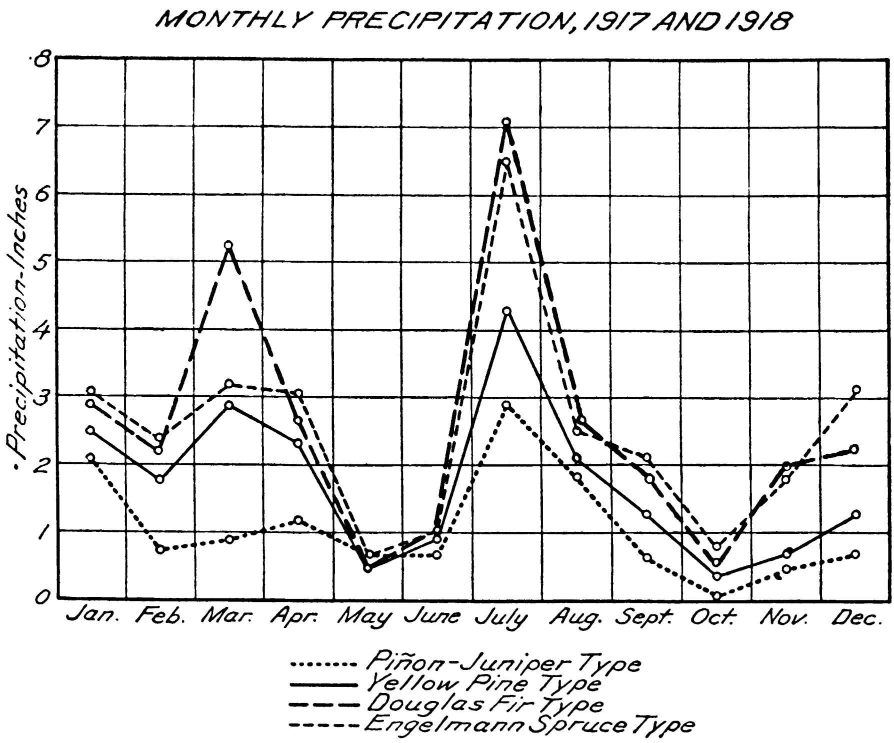

FIG. 5.

TABLE 9. *Precipitation*

	Alt. Ft.	Annual (inches)		June to September (inches)	
		1917	1918	1917	1918
Desert-Grassland					
Kingman	3,300	9.67	13.00	2.25	3.70
Winslow	4,850	7.38	....	4.93	....
Pinon-Juniper					
Ash Fork	5,100	13.99	12.36	7.05	5.21
Cosnino	6,500	....	....	4.91	8.40
Yellow Pine					
Williams	6,750	26.06	32.50	7.34	9.21
Walnut Canyon	6,700	....	....	6.65	7.45
Flagstaff	6,900	18.82	21.29	8.82	10.06
Fort Valley	7,300	17.81	24.27	7.43	9.89
Douglas Fir	8,900	23.60*	37.11*	12.21	12.95
Engelmann Spruce	10,500	....	....	....	....
N. W. Slope, cover	....	....	....	....	8.76
S. W. Slope, open	....	25.49*	35.16*	11.09	12.84
Alpine	11,500	....	40.23*	....	15.35

* Probable error of 1 to 2 inches due to inaccuracies in snow measurements.

Depth and duration of snow increase with altitude throughout the entire range. In the pinon-juniper type, snowfall is light and rarely stays on the ground more than a week at a time. In the yellow pine type it accumulates through the winter to a depth to 2 to 4 feet, but usually is all gone by April 1. In the Douglas fir type it becomes 3 to 4 feet deep and persists until about May 1. In the Engelmann spruce type the depth commonly reaches 6 feet and it stays on until the middle of June. In the alpine type the depth is uneven on account of drifting, the average being about 6 feet; it persists until the middle of June and in sheltered spots until the middle of July.

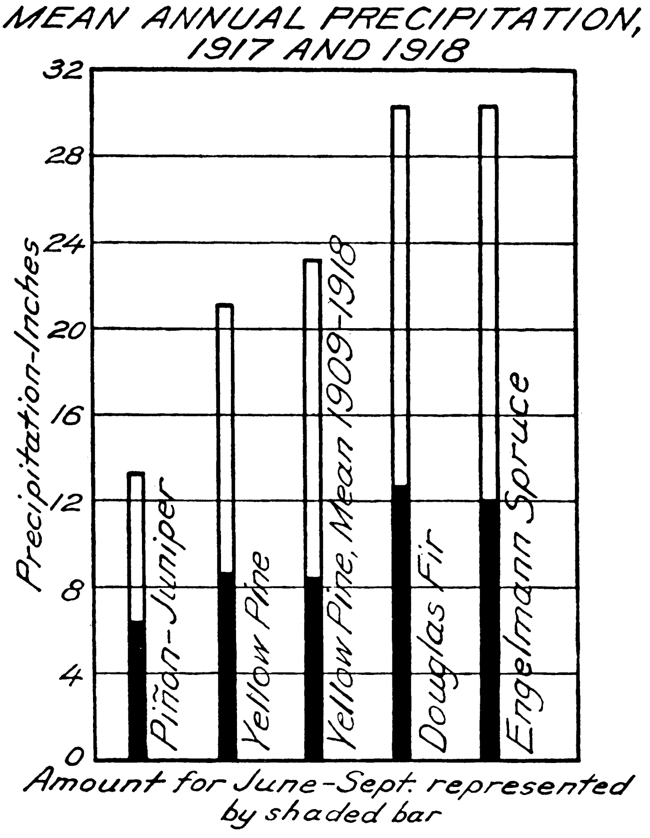

FIG. 6.

Throughout the range of forest types there are two periods of rather heavy precipitation separated by pronounced dry periods. The heavy snows leave the soil saturated with moisture which constitutes practically the entire supply until the advent of the summer rains in July. Intense drought usually prevails below the Douglas fir type through May, June, and the first half of July. During this period all but the deep rooted plants dry up, many stock watering places go dry, and the danger from forest fires is great. In the types above the yellow pine, although precipitation in April, May and June is light, the slowly melting snow keeps the soil moist. In the Douglas fir type there may be signs of drought in the latter part of June, but in the Engelmann spruce and alpine types the soil is usually moist right up to the beginning of the summer rains. The driest period in the Douglas fir and Engelmann spruce forests is usually in October and November.

Wind and Evaporation.—Wind movement near the ground is determined mainly by the density of forest cover. The highest records are obtained in the alpine type, due mainly to the absence of forest cover. The lowest movement is recorded in the Engelmann spruce type where, on account of the dense forest, wind is scarcely discernible except at the tree tops. High velocities are the rule in the pinon-juniper type, owing to the fact that the trees are low and more or less scattering. In the yellow pine type high winds are experienced on clear-cut lands and other areas devoid of forest, but within stands of virgin timber wind movement is relatively light. The Douglas fir type is mostly free from high winds because areas on which the coniferous forest has been destroyed have grown up to aspen. Records for September, 1918, are given in Table 10.

Table 10. *Evaporation and wind*

Forest types	Evaporation from water surface, total inches		Wind movement, total miles	Ratio of evaporation to precipitation
	June to September		June to September	June to September
	1917	1918	1918	1918
Pinon-Juniper				
Ash Fork	....	41.95	.....	8.06
Yellow Pine				
Walnut Canyon	....	27.12	.....	3.66
Fort Valley	22.28	18.54	6,661	1.87
Douglas Fir	18.96	15.40	.....	1.19
Limber and Bristlecone Pine*	....	....	19,939	....
Engelmann Spruce*				
N. W. Slope, Dense cover	....	6.30	4,930	0.72
S. W. Slope, Opening	....	16.58	.....	1.29
Alpine*	....	19.34	23,494	1.26

* Interpolated June 1 to 13.

Evaporation is controlled mainly by temperature, relative humidity and wind. At some stations these factors combine so as to create high evaporation; at others the opposite effect is produced; while at still others one factor tends to neutralize the other. In the pinon-juniper we have high temperature, high wind movement and low relative humidity. The evaporation here is by far the highest recorded for any of the forest types (Table 10 and fig. 7). In the dense Engelmann spruce forest we have exactly reverse conditions, namely low temperature, practically no wind, and high relative humidity, with the result that this station has the lowest evaporation.

In the alpine type the low temperature favors low evaporation, but is counteracted by high wind movement, and as a result evaporation is relatively high.

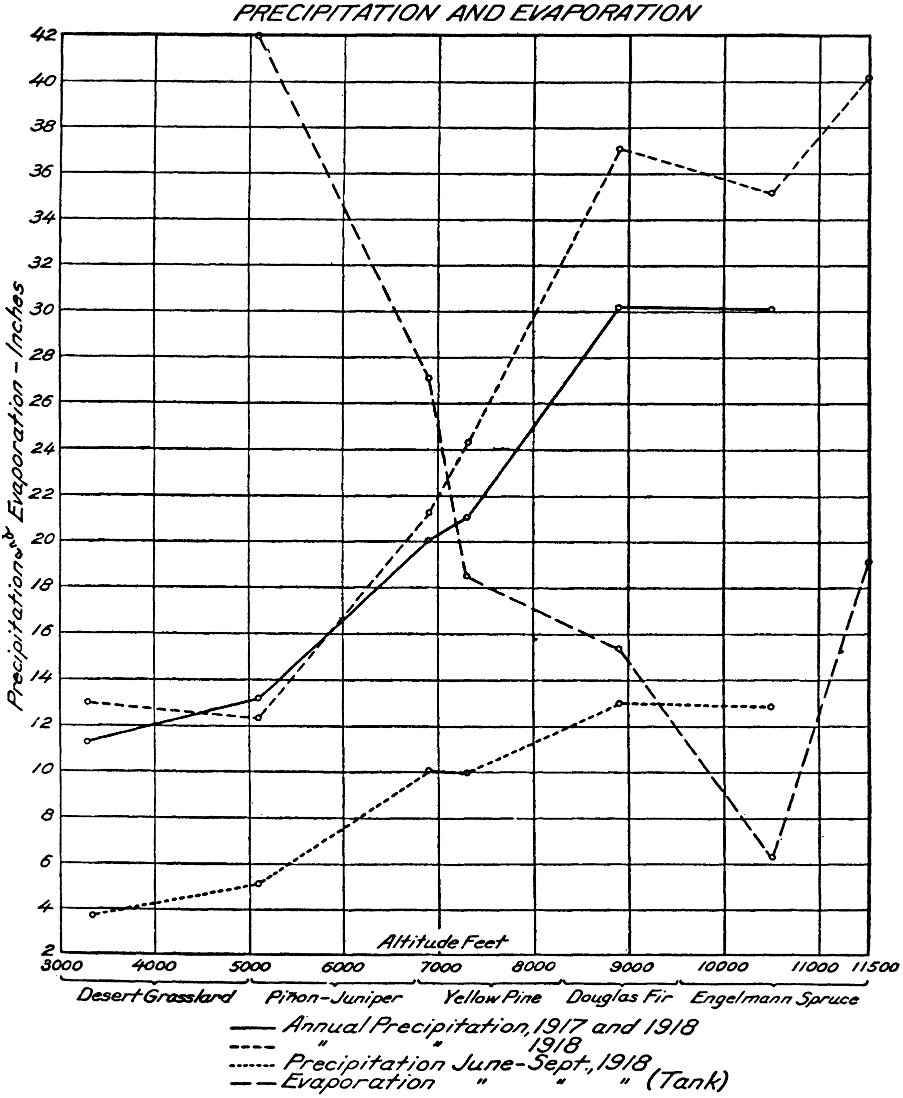

FIG. 7.

SOIL.—*Origin and General Character.*—On the basis of origin several general soil types occur in this locality, as determined by the rocks from which they are derived, mainly sandstones, limestones, basalt, dacites, andesites and ryolites.

In the pinon-juniper type we have soils derived from sandstones, limestones and basalt. The sandstones form a light sandy soil; the limestones usually form a fairly light surface soil, but a subsoil of clayey texture. The basaltic soils vary from a clay loam to a clay; and, unless mixed with a large proportion of gravel and rocks are somewhat impervious to roots and water.

Basaltic soils prevail over the greater portion of the yellow pine type. As in the pinon-juniper type they are of a compact, impervious structure unless, as is frequently the case, this condition is relieved by the admixture of gravel and stones. Sandstone and limestone soils similar to those described above occur locally in the lower half of the yellow pine type. Toward the upper limits of the type the soils are derived from a variety of volcanic rocks. These soils, since they occupy steep mountain slopes, are generally gravelly and stony throughout and are therefore very porous and easily penetrated by tree roots. They contain considerable humus in the surface layer, and grade into the succeeding belts of Douglas fir and Engelmann spruce.

Above the yellow pine type in the San Francisco Mountains the soil is almost entirely derived from volcanic rocks. In the Douglas fir and Engelmann spruce types the surface foot contains an appreciable amount of organic matter which, however, becomes less conspicuous as the alpine type is approached. In the Engelmann spruce type we find a forest mould from 2 to 4 inches thick. This is also present in the Douglas fir type, but here it is much thinner and less thoroughly decayed than in the Engelmann spruce type. In the pinon-juniper and yellow pine types, anything approaching a true forest mould occurs only close around the trees, and even here a large part of the material is undecayed.

Chemical analyses of the various soil types occurring in the San Francisco Mountains region reveal no difference of especial significance as related to vegetation. All are productive when supplied with sufficient moisture, and as far as can be determined the chemical composition is not an important factor in determining the distribution of species within the same climatic belt or vegetative zone. All the information at hand points to available moisture, as determined mainly by physical composition, as the dominant soil factor. As has been stated in previous publications[10] the admixture of sand, gravel and stone is believed to be vital in the adobe soils which without these constituents tend to become impermeable to both water and roots.

Soil Moisture.—Figure 8 shows the available soil moisture in the various forest types during the growing season of 1918. The plotted values represent the net percentages above the wilting point as determined by the centrifugal method of Briggs and Shantz[11] and computed according to their formula as modified by the Office of Dry Land Agriculture. The wilting point determinations are based upon too small a number of samples, and, moreover, the distribution of rainfall during the growing season of 1918 was considerably better than usual. For these reasons the data on soil moisture are not considered thoroughly satisfactory.

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[10] Pearson, G. A., "Studies of Yield and Reproduction of Western Yellow Pine in Arizona and New Mexico," Journal of Forestry, Vol. 16, No. 3, pp. 273–293, 1918 (especially p. 287); "The Relation between Spring Precipitation and Height Growth of Western Yellow Pine Saplings," idem, Vol. 16, No. 6, pp. 677–689, 1918 (especially p. 687).

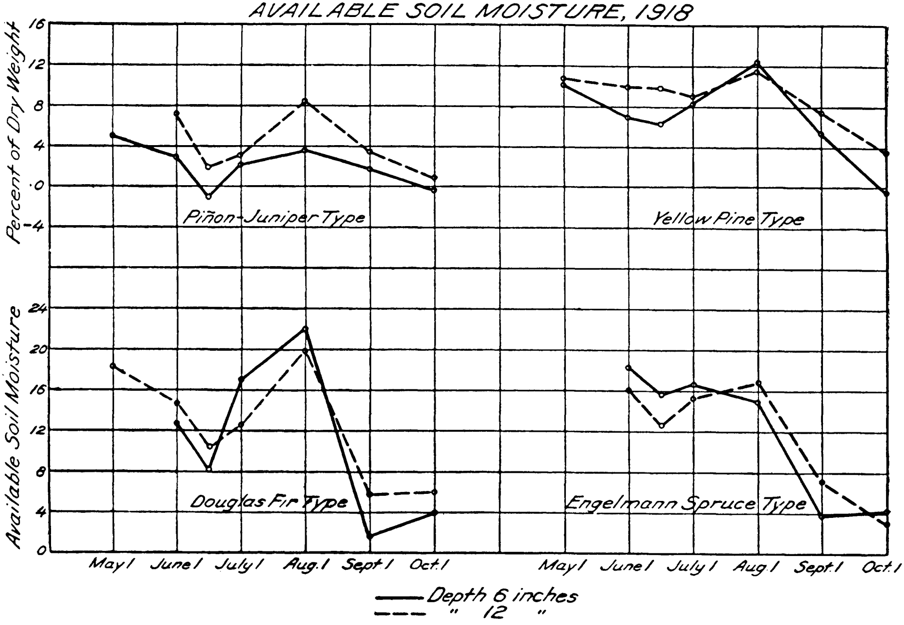

Fig. 8.

During the rainless period of May and June in 1918 moisture values approaching the wilting point at depths 6 inches or more below the surface were recorded only in the pinon-juniper type. In years of normal rainfall it is probable that equally low depressions occur in the yellow pine type. In the Douglas fir and Engelmann spruce types there is in normal years an abundance of soil moisture throughout this period, due to the deferred melting of snow which in the spruce forest persists into the month of June. It is the stored moisture resulting from the winter's snows which enables plants to live at all through May and June in the yellow pine and pinon-juniper types. In 1918 the early advent of the summer rains restored the rapidly declining moisture content in time to prevent its sinking to the low level which is reached in years when the summer rains begin from 2 to 4 weeks later. In 1918 the soil became driest about October 15, while in 1917 the lowest point was reached about December 31. Especially significant is the reduction in the lower strata even in the Engelmann spruce and Douglas fir types. Although the rainfall from June 15 to August 31, 1918, was close to 12 inches in both the Douglas fir and the Engelmann spruce types, the moisture content at a depth of 1 foot on October 1 was but slightly above the wilting coefficient. From this condition it is surmised that in all the forest types, regardless of rainfall, there is a tendency to exhaust the entire moisture supply during periods of active growth. Such a situation is conceivable when we consider the luxuriant vegetation in the types of heavy rainfall. If the results of this year's investigations are supported by measurements in 1919, it may become established that the most critical drought period for reproduction of all species is not in the fore-summer but in the fall. The data already at hand prove this to be the case for Douglas fir and Engelmann spruce but whether it is true of western yellow pine and pinon-juniper is less certain.

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[11] Briggs, L. J., and Shantz, H. L., "The Wilting Coefficient of Different Plants and its Indirect Determination," U. S. Dept. Agr. Bu. Pl. Ind. Bul. 230, 1912.

Table 11. *Soil temperature at 1 foot depth*

	Alt.	Aspect	Cover	Temperature degrees F.			
				Annual		May–Oct.	July–Oct.
				1917	1918	1918	1918
Pinon-Juniper							
Ash Fork (W)	5,100	Level	Open	....	....	71.2	72.6
Cosnino (E)	6,500	“	“	....	....	66.5	66.9
Yellow Pine							
Walnut Canyon	6,700	“	“	....	....	66.2	66.6
Fort Valley	7,300	......	......	....	....	......	....
Open	....	“	“	....	49.6	62.5	63.2
Partial Shade	....	“	Partial shade	....	45.7	56.2	57.6
Heavy Shade	....	“	Heavy shade	43.1	43.7	53.1	54.5
Douglas Fir	8,900	....	......	....	....	......	....
Last Y. Pine	8,900	South	Open	....	....	......	55.7
Forest	....	N.W.	Partial shade	39.6	40.8	48.8	49.6
Limber-Bristlecone	10,000	S.W.	Open	....	....	54.2*	54.2
Engelmann Spruce							
Forest	10,500	N.W.	Dense shade	34.9	35.2	40.8	43.4
Opening	....	S.W.	Open	....	....	47.0*	49.1
Alpine	11,500	W.	“	....	....	......	45.5

* Interpolated in part.

Soil Temperature.—Like mean air temperature, soil temperature (Table 11) falls with rising altitude. It furnishes a fairly good index to available heat energy. The bare soil is a good heat absorber, and at a depth of one foot or more it loses heat slowly. During the snowless period, soil temperatures taken in the open down to 6 inches in depth are usually several degrees higher than the mean or even the maximum air temperatures. During the period when the ground is continuously covered with snow, the soil temperature remains constantly at or a few degrees below 32° F. at all stations and at all depths down to 2 feet.

Experience has shown the selection of the site for soil thermometers to be exceedingly important. Exposure to the sun is the greatest factor. The difference in soil temperature between a north and a south exposure is much greater than the corresponding air temperature difference. The degree of shade as determined by crown cover is of tremendous importance. As shown by the records for "Open" and "Heavy Shade" at Fort Valley, in the yellow pine type (Table 11), the temperature at one foot is 6 to 9 degree F. lower in the shade of a group of trees than in an adjoining opening less than 100 feet away.

The diurnal fluctuation for depths of one foot is usually not more than 2 or 3 degrees F. In a moderately dense forest it is less than 1 degree. At the surface in the open it is much higher than the diurnal range of air temperature.

Since the soil temperatures at the mountain stations are based mainly upon weekly readings, except at the 6-inch depths for which thermographs are provided, many readers may question the reliability of the data presented in Table 11. Check readings at various times have shown that the error from this source is less than might be expected. The table below gives a comparison of means obtained by weekly and daily readings at the yellow pine station during the months of May and June, 1919. The differences at this season are as great as would be obtained at any other time of the year, and greatly exceed those of the winter and midsummer months.

Mean Soil Temperature (°F.)

	Heavy cover		Opening	
	Weekly readings	Daily readings	Weekly readings	Daily readings
May				
1st decade	43.1	43.5	49.1	49.8
2d decade	45.5	46.4	57.6	59.4
3d decade	49.7	48.7	58.5	57.3
Month	46.1	46.2	55.1	55.5
June				
1st decade	49.1	48.8	57.4	56.9
2d decade	52.7	53.1	66.7	66.0
3d decade	58.8	58.8	70.9	70.2
Month	53.5	53.6	65.0	64.4

The comparison shows a maximum error of 1.8° F. for a single decade in the open, and 1° under the cover of a group of trees. The maximum errors in the monthly means are 0.6° in the open and 0.1° under cover. The errors at the mountain stations would be less than those here indicated, because of generally lower temperature extremes, and in some instances because of denser forest cover. During periods when the ground is covered with snow, the error due to infrequency of readings is negligible.

(*To be concluded*)